REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
15JUL98

3. REPORT TYPE AND DATES COVERED
SBIR phase I final report, 1SEP97 - 31MAY98

4. TITLE AND SUBTITLE
30% Efficient Three Junction Solar Cells
for Space Concentrator Modules

5. FUNDING NUMBERS
Contract #: NAS3-97180

6. AUTHOR(S)
Dr. Lewis M. Fraas, PI
James E. Avery

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
JX Crystals Inc.
1105 12th Avenue NW, Suite A2
Issaquah, WA 98027-8994

8. PERFORMING ORGANIZATION REPORT NUMBER
BMDO97FNL

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Supported by Ballistic Missile Defense Organization/Science and Technology, and managed by the NASA Lewis Research Center. Opinions and findings expressed in this material are those of the authors and do not necessarily reflect the views of BMDO or NASA.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

19980724 054

13. ABSTRACT *(Maximum 200 words)*
Report developed under SBIR contract. The benefits of mechanically stacked tandem concentrator solar cells were first demonstrated on a NASA mission in 1994. In that case, transparent GaAs cells were stacked on top of infrared-sensitive GaSb booster cells and arrayed in a point-focus solar concentrator module. The results were high efficiency, excellent radiation resistance and high voltage tolerance, all of which sustained some interest in concentrator arrays. Since then, the lens design has evolved to a linear geometry used with high efficiency non-transparent GaInP2/GaAs cells on germanium substrates. These high bandgap dual junction cells still leave about 35% of the sun's longer wavelength energy uncollected. The proposal for this contract was to make the dual junction cell transparent to that long wavelength range and stack it on a GaSb booster cell for added efficiency gains. Tecstar made the transparent dual junction GaInP2/GaAs cells on GaAs substrates as a subcontractor, and JX Crystals took on the tasks of booster cell fabrication as well as assembly and testing for this Phase I effort. Resulting dual junction cells achieved efficiencies of 29.6% at a 15 sun concentration level.

14. SUBJECT TERMS
SBIR report, photovoltaic, gallium antimonide, GaSb, infrared, IR, concentrator, solar

15. NUMBER OF PAGES
16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

Summary

High bandgap GaInP/GaAs Dual Junction cells have been developed for aerospace production on Germanium substrates that increase efficiency by several points compared to single junction GaAs/Ge. In either case 35% of the sun's energy below the bandedge of GaAs remains uncollected. Efficiency gains have been demonstrated previously for the case of Transparent GaAs grown on a GaAs substrate and then mechanically stacked on top of a lower bandgap GaSb Infrared Booster Cell. For example on a prior NASA contract, we demonstrated 25% efficient power circuits containing 24 GaAs/GaSb cell stacks operating at 25 suns concentration. In these circuits, the GaAs cells contributed approximately 20 percentage points and the GaSb cells provided a boost of 5 percentage points to arrive at the 25% overall conversion efficiency. The objective of the present contract was to increase efficiency even further by replacing Transparent single junction GaAs with Transparent Dual Junction GaInP/GaAs. Tecstar fabricated and delivered several Transparent Dual Junction cells which were assembled at JX Crystals in mechanical stacks on top of GaSb booster cells. At 15 suns a Dual Junction cell efficiency of 23.3% combined with a 6.3% boost from the GaSb added to a total of 29.6% which is a significant 4 point increase over the previous case. This new high efficiency configuration is compatible with arrays such as SCARLET which use linear concentrating optics and operate in the range 5 to 30 suns.

Introduction

The benefits of mechanically stacked tandem concentrator cells were first demonstrated by the PASP program. In that case single junction Transparent GaAs cells were stacked on top of GaSb booster cells and arrayed with Entech's domed Fresnel Lenses and Optical Secondaries. High efficiency, excellent radiation resistance and high voltage tolerance sustained some interest in concentrator arrays. Since then the lens design has evolved to a Linear geometry used with high efficiency non-transparent $GaInP_2$/GaAs cells on Germanium substrates. These high bandgap dual junction cells still leave about 35% of the sun's longer wavelength energy uncollected. The proposal for this contract was to make the Dual Junction cell Transparent to that long wavelength range and stack it back on a GaSb booster cell for added efficiency gains. Tecstar agreed to make some Transparent Dual Junction $GaInP_2$/GaAs cells on GaAs substrates as a subcontractor on this project. JX Crystals mass produces GaSb cells for ThermoPhotoVoltaic products and took on the task of booster cell fabrication as well as assembly and testing for this Phase I effort.

Design

A four terminal configuration with one dual junction $GaInP_2$/GaAs top cell and one GaSb bottom cell was chosen for this project so that each cell could be tested independently. After agreeing on a nominal 1 cm^2 illuminated area, cells were designed separately at Tecstar and JXC with dimensions and ohmic bar locations allowing for active area alignment and interconnect bonding. Specific cell designs are illustrated in Figure 1. Photolithography mask sets were designed and ordered at each location. The Tecstar cell involves metal lift off for front and back metal, a trench etch to define active area and an AR coating lift off. The JXC cell has a front metal pattern and a diffusion mask. The active areas of the cells with junctions and grid lines is well defined by the photomasks. The JXC cell is 1.14 cm^2 and the Tecstar cell is 1.12 cm^2.

Also shown in Figure 1 is the printed circuit board substrate design and a final assembly drawing. The backside ohmic bar on the Tecstar cell wound up on the side opposite what was initially expected. Fortunately the substrates hadn't been ordered yet and the design was modified to accommodate this change. The final configuration is actually more consistent with a linear array where top cell contacts might both be along one edge and bottom cell contacts along the opposing edge of a long strip. Top cell symmetry allowed this change with the only downside being some extra non-active area on the side opposite the ohmic bars and a negligible difference in active area alignment. Substrate dimensions of 1" x 1" were chosen to keep the package small enough for calibration testing on the NASA Lear jet or JPL balloon flights and for possible testing with a concentrating lens at Entech. Tecstar supplied a few of their bypass diodes and these were integrated into the assembly to protect the front cell from inadvertent destructive biasing during testing.

Cell Fabrication

The GaSb cells were fabricated at JXC using exactly the same processes and procedures that are well established for our TPV cell production, the only difference being the photomask set. The sequence includes junction formation by diffusion, AR coating and lift-off metallization. The first wafer through processing had a perfect yield of 8 cells whose performance was as good as could be expected based on a large history. We weren't sure how many cells Tecstar would deliver so we stopped with 8 goods cells in-hand. Summary performance data near 15 suns is shown in Table 1. All of the characteristics are tightly grouped, less than 1.5% worst case standard deviation. This result is typical for JX Crystals GaSb production.

Tecstar had a number of development issues involved in making a transparent dual junction cell. Their $GaInP_2$/GaAs Cascade cell production epi layers are normally grown on a low bandgap Germanium substrate. In order to transmit long wavelength energy through to our GaSb cells they had to switch over to a low doped GaAs substrate, add a gridded back side metallization, add a back side AR coating and do a front to back pattern alignment. Additionally, they included a lift off mask for the AR coatings on both sides to keep the ohmic bars clean for bonding and a trench etch mask to accurately define the active junction area. The trench etch also isolates any non-gridded junction on the upper surface which is a benefit in testing. On a previous contract without the trench an erroneous fill factor was recorded due to some non-gridded area with very high series resistance in parallel with properly gridded area.

They procured GaAs wafers in the $10^{16} - 10^{17}$ cm^{-3} doping range and processed the cells and optical filters that will be described below. The epi layers were grown in a production reactor where growth schedules are designed for Ge substrates. Limited access precluded any attempt to optimize the schedule for GaAs substrates at this time. The AR coatings also were deposited in a production machine, which again did not allow for any specific optimization for this project.

Tecstar wound up delivering 10 cells for this contract. The 1 Sun AM0 performance data of these cells, measured at Tecstar, is presented in Table 2. At 1 sun the characteristics are tightly grouped with efficiencies of 22-23%.

Optics

The GaSb cell boost efficiency in a mechanical stack is quite dependent on the optical transmission through the high bandgap top cell at wavelengths longer than the GaAs bandedge of about .86 microns. Since we haven't ever seen the optical characteristics of transparent $GaInP_2$/GaAs we asked Tecstar for a dual junction filter, that is, a piece of GaAs coated with the same epi layers and AR

coating used on the cells but with no patterning or metallization. They delivered a large piece of filter material as well as their measured Transmission and Reflectance curves, which are shown in Figure 2 and 3. Notice the average transmission near 70% in the GaSb collection band from .86 to 1.8 microns and the average reflectance of about 30%. Since these add up to near 100% we can deduce that there is very little absorption in this filter. We believe that a 10^{17} doped wafer was used in this case. The cells are probably about the same with an additional loss due to grid coverage of about 10%.

There may be some room for improvement on optical performance. With dedicated equipment and some development time GaAs filter transmissions over 90% were achieved for the PASP project as shown in Figure 4, albeit for a single junction case. Tecstar was limited this time around to production coating runs of 2 layer TiO_x/Al_2O_3.

The relative transmission compared to the dual junction filter of the 10 delivered Tecstar cells was tested by setting each cell temporarily on top of a GaSb cell and measuring Isc. Data is tabulated below in Table 3. 8 of the cells yielded about 90% transmission compared to the filter, which is the expected result for 10% grid coverage. 2 of the cells, #62 and #67, are quite a bit lower, only 67%. These 2 low transmission cells were excluded from further consideration.

Test Methods

All of the concentrated light IV performance data in this report was measured at JXC with an in-house flash lamp solar simulator. This simulator has a long arc xenon flash tube with a specified color temperature of 6400K, which should be a reasonable approximation of AM0 sunlight. It is the same model used for PASP testing several years ago in which case the blue/red ratio was well characterized using Lear Jet and JPL balloon standards of GaAs and stacked GaSb cells. In that case the ratio was near perfect and yielded the proper Isc in both cells at the same time. Of course we understand the need for calibration given a new front cell epi structure with 2 junctions and a different AR coating, so our new results may be considered preliminary.

For this project the light intensity for both cell types was calibrated using Tecstar cells and the 1 sun short circuit currents measured at Tecstar. The lamp was adjusted to yield about 15 times the 1 sun values and the Isc of a separate GaAs monitor cell on the same test plane was recorded. A monitor cell value corresponding to 15 suns was then computed from an average of the Tecstar current ratios. The intensity used for calculating efficiencies in the range 5-50 suns was then determined from monitor cell ratios. This approach assumes that the Isc of the Tecstar cells, the GaSb cells and the GaAs monitor are linear functions of light level. In fact 2 of the Tecstar cells had noticeably lower Isc near 15 suns than the rest and these cells were not included in the calibration of the monitor.

Tecstar Screening Tests

Upon receipt the 10 Tecstar cells were tested near 15 suns. Summary data is shown in Table 4 and IV curves are charted in Figure 5. In contrast to the 1 sun data there is obviously an increased variability in performance parameters at the higher light level except for Voc which remains tightly grouped. Efficiencies range from 14.9 % to 23.3%. We chose the best 4 cells for assembly, #47 #43 #41 and #34. #62 and #67 are fairly good but had low optical transmission.

The best cell, #47, was measured at various light levels from 5 to 50 suns. 5 suns is the lower limit of the JXC tester at this time. Performance data is given in Table 5 and charted on a log scale in Figure 6. Tecstar's 1 sun values are included. Voc increases with light level throughout this range and Voc versus the log of concentration is near linear. FF peaks near 5 suns and then starts to droop. Efficiency peaks at 5 suns, the maximum value being 23.5% in this data set. Efficiency is over 23% from 5 to 20 suns.

GaSb Testing

One GaSb cell was tested in the range 10 to 50 suns. Summary data is shown in Table 6 and performance parameters are charted in Figure 7. Voc increases throughout this range. FF peaks near 20 suns and then starts to droop. The grid pattern was designed for 15 suns so this is an expected result. Efficiency peaks near 30 suns at 6.5%. We know from TPV testing that these results will be typical for all of the cells.

Assembly

The process of assembling the cell pairs included the following sequence of steps:

- die bond the GaSb cell and bypass diode to the substrate
- interconnect the GaSb ohmic bar to the substrate
- bond top and bottom leads to the Tecstar cells
- stack the Tecstar cell on top of the GaSb cell with silicone adhesive
- bond the top and bottom Tecstar cell leads to the substrate
- add pigtail wires for testing
- clean

We started the 4 best Tecstar cells into assembly and broke 1 so we wound up with 3 finished test articles.

All of the required lead attachments were accomplished by soldering.

Stack Testing

The 3 finished assemblies were tested near 15 suns. Summary data is shown in Table 7. Combined efficiencies of 27.8% 29.6% and 28.9% were recorded. IV curves for each cell in the 3 stacks are charted in Figures 8 and 9.

Deliverables

Figure 10 shows a photograph of the 3 finished stacks which are now packaged and ready for shipping.

Conclusions

Tecstar's first attempt to make Transparent Dual Junction $GaInP_2/GaAs$ concentrator cells for this Phase I effort resulted in a best cell efficiency over 23% at 15 Suns AM0. This is well within the efficiency range of the non-transparent Cascade cells that they delivered for SCARLET and suggests that equivalent performance may be possible. JX Crystals was able to supply GaSb Booster Cells using existing production processes. When stacked together this pair of cells adds up to 29% efficiency which is a full 4 or 5 percentage points better than the Cascade cell by itself.

Recommendations

Consider pulling together a team effort to make a 30% efficient linear concentrator flight test array element with Transparent Dual Junction on GaSb Booster Cell stacks.

References

[1] Murphy, D., Eskenazi, M., "SCARLET: Design of the Fresnel Concentrator Array for New Millenium Deep Space 1," 26th IEEE-PVSC, 1997.

[2] Bertness, K.A., Kurtz S.R., Friedman D.J., Kibbler A.E., Kramer C., Olson J.M., "High-Efficiency $GaInP_2/GaAs$ Tandem Solar Cells for Space and Terrestrial Applications," 1st WCPEC, 1994

[3] Fraas, L., Final Contract Report NAS3-27240

[4] Keener D., Marvin, D., Brinker, D., Curtis H., Price, P., "Progress Toward Technology Transition of $GaInP_2/GaAs/Ge$ Multijunction Solar Cells," 26th IEEE-PVSC, 1997

	FF	Voc (volts)	Isc (amps)	Imax (amps)	Vmax (volts)	Pmax (watts)	Eff (%)
	0.722	0.426	0.477	0.419	0.350	0.147	6.32
	0.711	0.428	0.478	0.415	0.351	0.146	6.28
	0.712	0.428	0.485	0.433	0.341	0.148	6.36
	0.716	0.429	0.476	0.425	0.344	0.146	6.28
	0.714	0.430	0.474	0.417	0.350	0.146	6.28
	0.713	0.430	0.484	0.427	0.348	0.149	6.41
	0.719	0.430	0.472	0.422	0.346	0.146	6.28
	0.724	0.431	0.471	0.425	0.346	0.147	6.32
average	0.716	0.429	0.477	0.423	0.347	0.147	6.32
%stdev	0.67	0.37	1.08	1.39	0.99	0.77	0.77

Table 1. JXC GaSb Booster Cell Performance Near 15 Suns AM0

Cell#	Voc (volts)	Isc (amps)	FF	Eff (%)
34	2.36	17.2	0.85	23.1
37	2.36	17.4	0.82	22.7
38	2.36	17.1	0.85	22.9
41	2.36	17.5	0.82	22.7
42	2.36	17.5	0.81	22.4
43	2.37	17.3	0.83	22.7
47	2.37	17.3	0.84	22.9
48	2.36	17.5	0.82	22.7
62	2.35	17.7	0.82	22.9
67	2.35	17.6	0.82	22.7

Table 2. Tecstar Cell IV Data at 1 Sun AM0

Tecstar Cell ID	Transmission Compared to Filter (%)
34	94.2
37	92.3
38	92.9
41	91.7
42	88.1
43	87.9
47	89.8
48	89.6
62	67.3
67	66.9

Table 3. Tecstar Cell Transmission

Cell#	FF	Voc (volts)	Isc (amps)	Imax (amps)	Vmax (volts)	Pmax (watts)	Eff (%)
34	0.781	2.53	0.267	0.240	2.20	0.528	22.7
37	0.684	2.53	0.264	0.216	2.11	0.457	19.6
38	0.559	2.52	0.247	0.178	1.96	0.348	14.9
41	0.754	2.52	0.271	0.244	2.11	0.514	22.1
42	0.618	2.51	0.266	0.217	1.90	0.411	17.6
43	0.761	2.55	0.265	0.233	2.20	0.513	22.0
47	0.798	2.53	0.269	0.238	2.29	0.543	23.3
48	0.716	2.53	0.233	0.191	2.22	0.423	18.2
62	0.713	2.52	0.272	0.228	2.15	0.490	21.0
67	0.710	2.54	0.276	0.228	2.18	0.496	21.3

Table 4. Tecstar Cell IV Data Flash Tested Near 15 Suns AM0

Conx	FF	Voc (volts)	Isc (amps)	Imax (amps)	Vmax (volts)	Pmax (watts)	Eff (%)
1.0	0.840	2.37	0.017				22.9
5.1	0.832	2.49	0.089	0.081	2.29	0.184	23.5
10.2	0.818	2.53	0.176	0.157	2.31	0.363	23.4
14.9	0.800	2.55	0.257	0.234	2.25	0.525	23.2
20.3	0.789	2.56	0.351	0.317	2.25	0.711	23.0
29.6	0.771	2.59	0.512	0.461	2.22	1.021	22.6
49.4	0.727	2.61	0.854	0.772	2.10	1.617	21.5

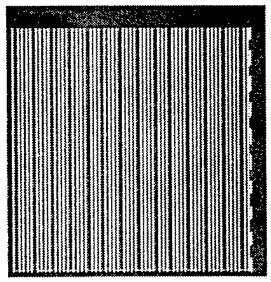
Table 5. Best Tecstar Cell Data Summary from 1 to 50 Suns AM0

Conx	FF	Voc (volts)	Isc (amps)	Imax (amps)	Vmax (volts)	Pmax (watts)	Eff (%)
9.7	0.699	0.421	0.311	0.274	0.334	0.092	6.11
14.7	0.705	0.435	0.471	0.406	0.355	0.144	6.31
19.3	0.707	0.441	0.617	0.549	0.351	0.193	6.46
28.9	0.697	0.454	0.924	0.827	0.354	0.292	6.52
49.7	0.670	0.467	1.589	1.466	0.339	0.497	6.46

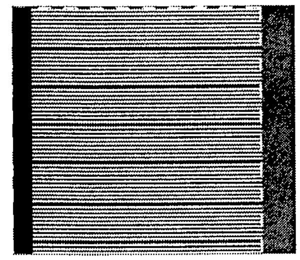
Table 6. GaSb Cell Data Summary from 1 to 50 Suns AM0

Type	FF	Voc (volts)	Isc (amps)	Imax (amps)	Vmax (volts)	Pmax (watts)	Eff (%)
GaInP/GaAs	0.749	2.50	0.257	0.232	2.08	0.481	21.2
GaSb	0.706	0.429	0.497	0.444	0.339	0.150	6.56
				Combined Efficiency of Stack # 3			**27.8**
GaInP/GaAs	0.803	2.54	0.264	0.237	2.27	0.538	23.3
GaSb	0.687	0.427	0.501	0.437	0.336	0.147	6.26
				Combined Efficiency of Stack # 4			**29.6**
GaInP/GaAs	0.774	2.54	0.259	0.232	2.20	0.510	22.3
GaSb	0.715	0.431	0.500	0.445	0.347	0.154	6.62
				Combined Efficiency of Stack # 5			**28.9**

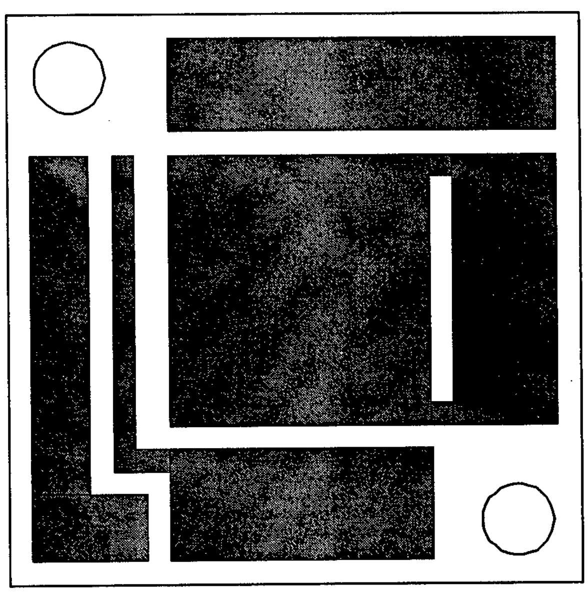
Table 7. Stacked Cell Flash Test Data at 15 Suns AM0



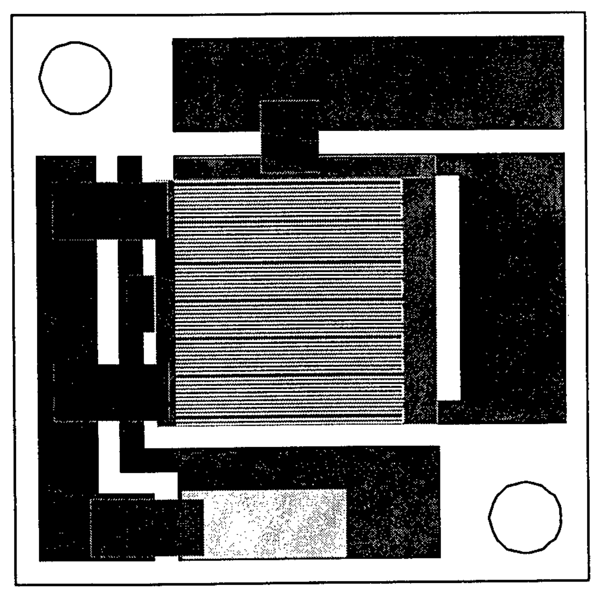
JXC GaSb Booster Cell
1.15 x 1.205 cm
1.14 cm^2 Active Area



Tecstar Dual Junction Cell
1.25 x 1.10 cm
1.12 cm^2 Active Area



PCB Substrate
2.54 x 2.54 cm



Mechanical Stack Assembly
with Bypass Diode

Figure 1. Illustration of Cells and Assembly Design

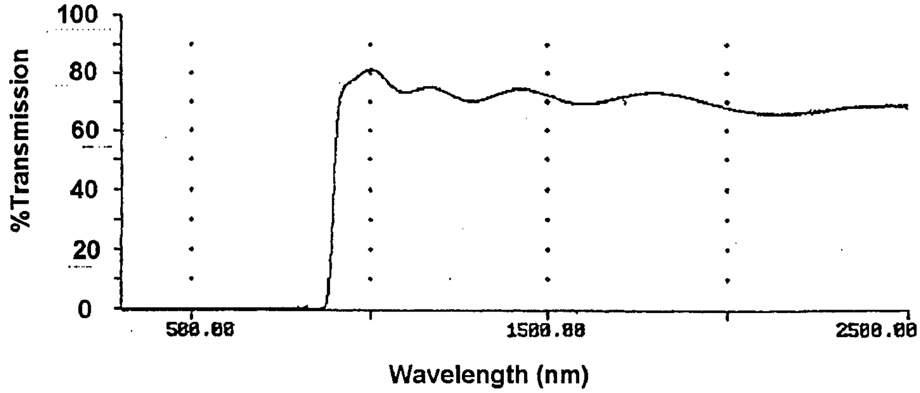


Figure 2. Tecstar Filter Transmission

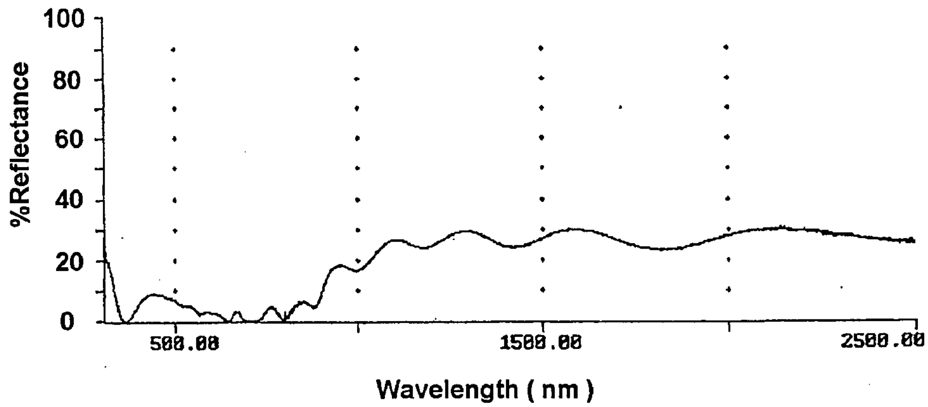


Figure 3. Tecstar Filter Reflectance

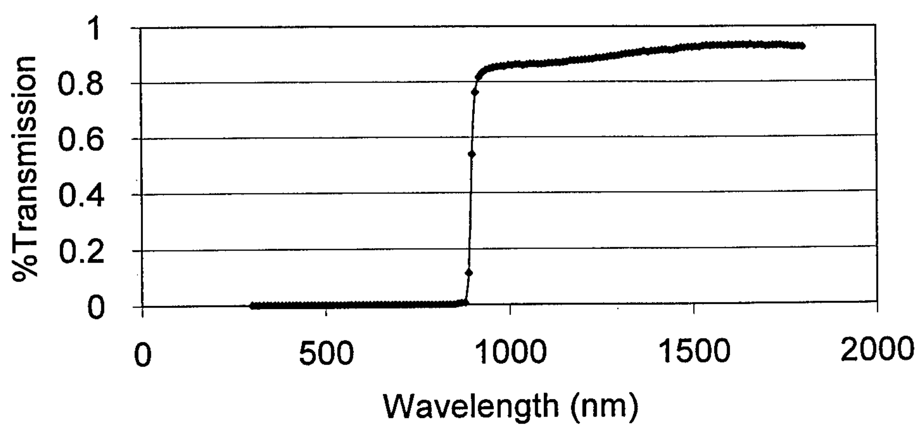


Figure 4. PASP GaAs Filter

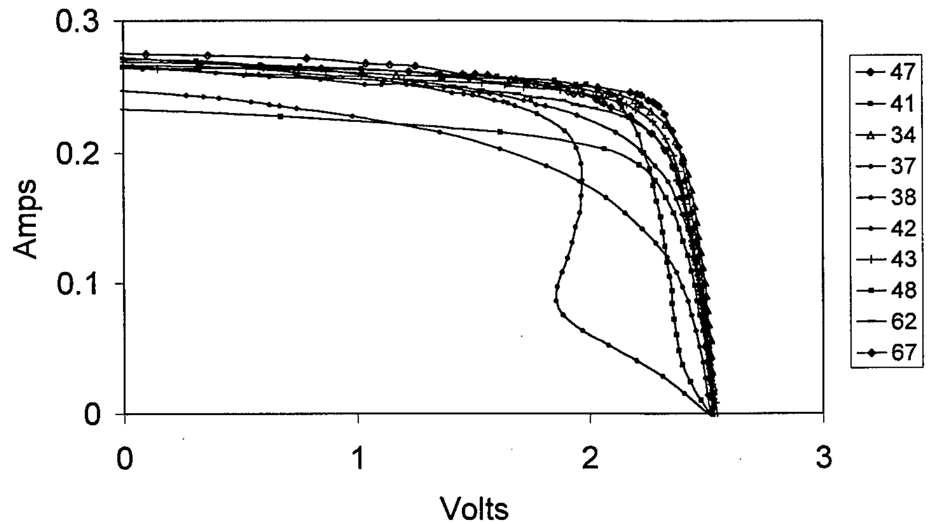


Figure 5. Dual Junction IV Curves Near 15 Suns AM0

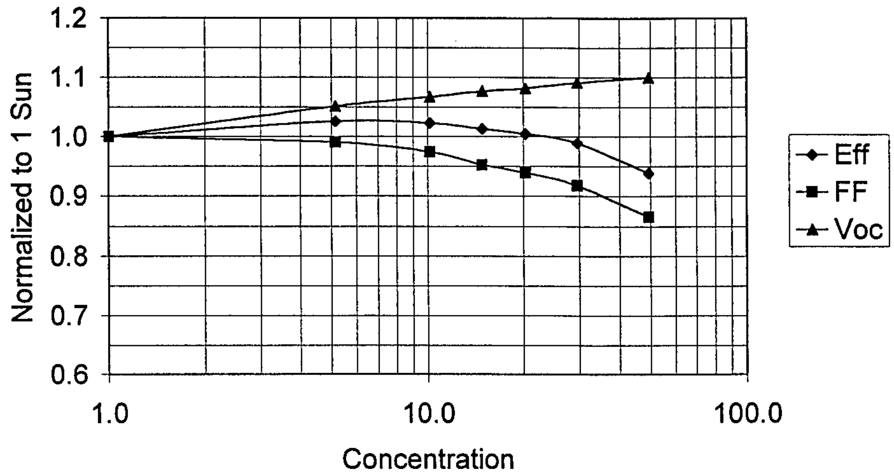


Figure 6. Best Tecstar Cell Normalized Characteristics versus Concentration

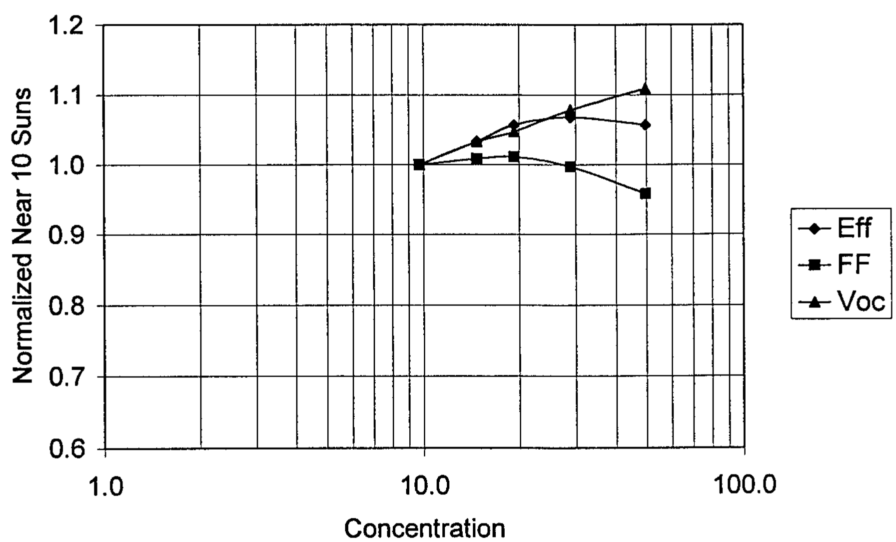


Figure 7. Normalized GaSb Performance versus Concentration

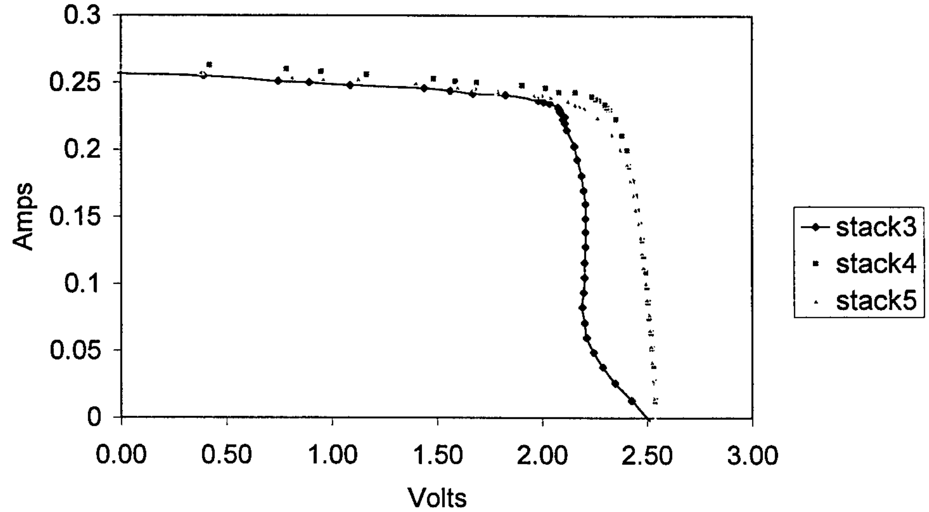


Figure 8. Assembled Tecstar Dual Junction IV Curves
at 15 Suns AM0

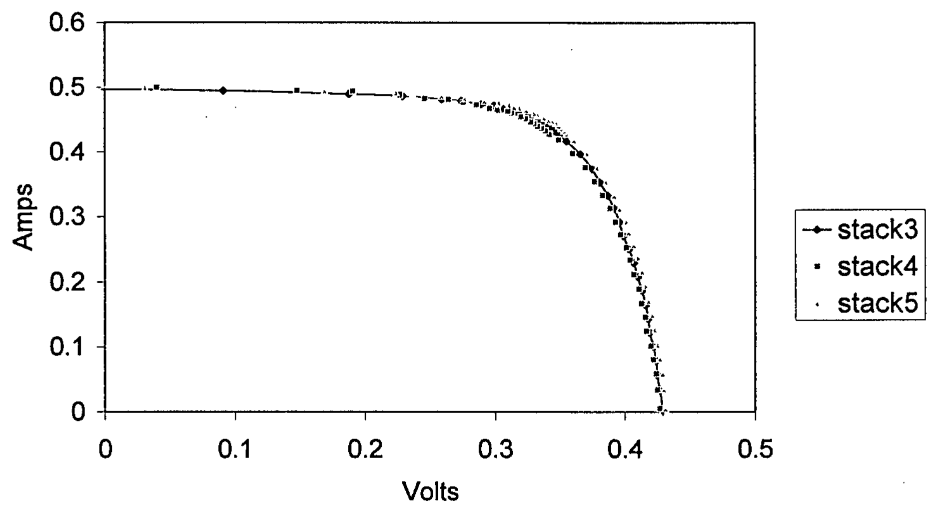


Figure 9. Assembled JXC GaSb Booster Cell IV Curves
at 15 Suns AM0

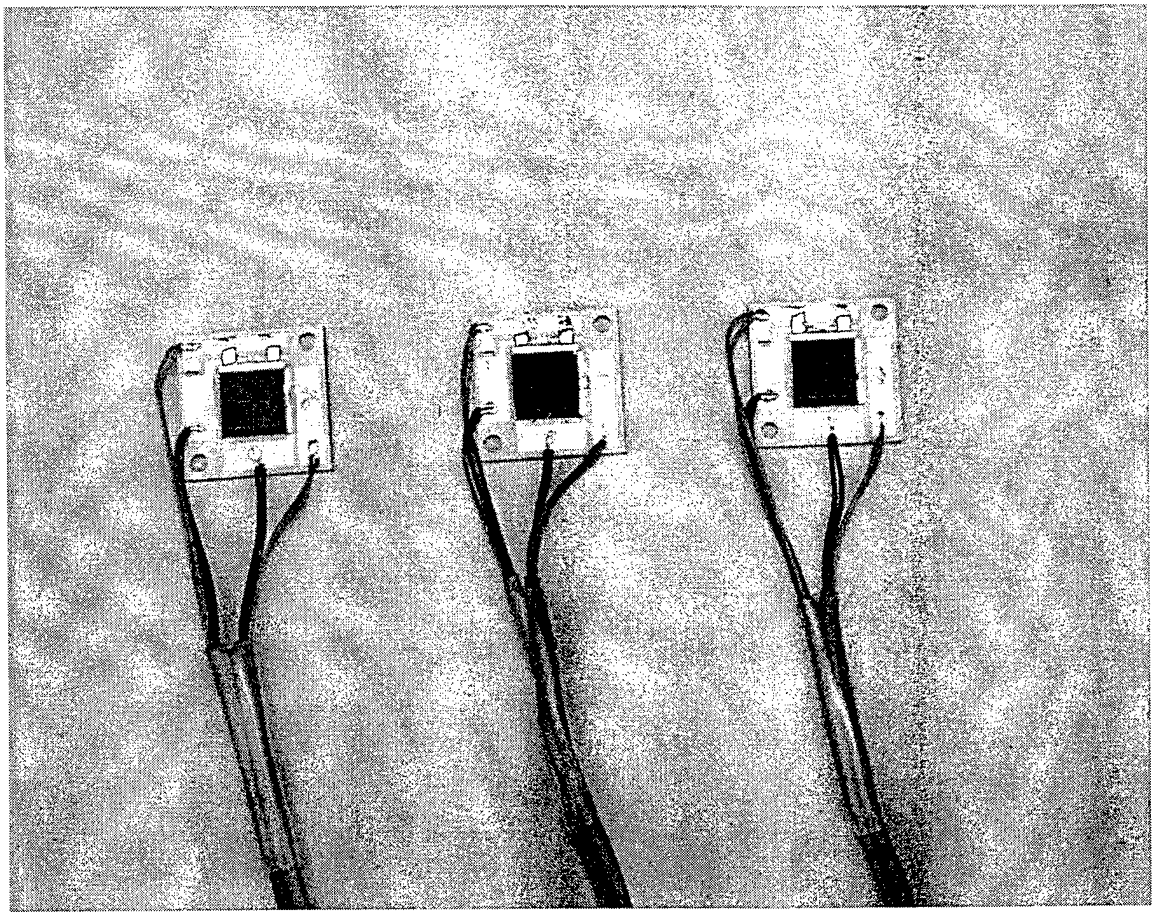


Figure 10. Dual Junction $GaInP_2/GaAs$ on GaSb Mechanically Stacked Test Articles

JX Crystals Inc.
1105 12th Ave. NW, Suite A2
Issaquah, WA 98027
(425) 392-5237
FAX: (425) 392-7303

July 20, 1998

DTIC
Attn: Document Acquisition
8725 John J. Kingman Road, Suite 0944
Fort Belvoir, VA 22060-6218

To Whom It May Concern:

Enclosed is one copy of the final report for our BMDO Phase I SBIR contract (contract no. NAS3-97180). We are sending a copy to you in accordance with section 12D of the contract.

This effort was very successful, and we are hoping to submit a phase II proposal in the near future. If it is of interest to you, please note that I have returned a New Technology Summary Report to Ms. Kathy Kerrigan in the NASA Lewis Commercial Technology Office as required. Please feel free to contact me at the number above if you have any questions. Thank you.

Sincerely,

Jason B. Keyes

Jason B. Keyes
Manager of Government Contracts

Enclosures